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An evaluation of economic and performance feedback in an inspection task with explicit economic consequences

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Abstract

Feedback has been consistently shown to improve inspection speed and accuracy, provided it is given in a timely and appropriate manner. Traditionally, this feedback has been with regard to speed and accuracy performance. Nevertheless, when there are explicit economic consequences associated with the inspection process, economic feedback is also an alternative. This study compares performance feedback with economic feedback in a realistic simulation of an aircraft inspection task. Subjects provided with performance feedback showed overall improvement in speed and accuracy. Subjects provided with economic feedback not only demonstrated similar improvement, but also approached economically optimal trade-offs between speed and accuracy.

Relevance to industry

The results of this study have direct implications on developing training strategies for improving industrial inspection performance. In particular, in the context of an aircraft inspection task, it was demonstrated that an appropriate training program could both improve accuracy (and therefore safety) and reduce the costs associated with inspection. These results are generalizable to other inspection applications in a variety of industries, such as electronics, textiles, manufacturing, and agriculture.

Keywords: Feedback; Visual search; Inspection

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1. Introduction

Visual search is an integral part of industrial inspection (Harris and Chaney, 1969; Wiener, 1986; Drury, 1992) and other time limited tasks (Greening, 1976). Applications of industrial inspection include visual inspection of integrated circuits (Schoonard Gould and Miller, 1973), sheet metal (Moraal, 1975), electronic chassis (Harris and Chaney, 1969, pp. 157–162), and airframe structures (Drury et al., 1990). While visual search is only one of the several inspection activities (e.g., Wang and Drury, 1989), it is arguably the most important as it has been shown, both theoretically and experimentally, to be the most time consuming and error prone (Drury, 1994).

A visual search task has two primary characteristics: speed and accuracy. Speed refers to the time required to complete the task, whereas accuracy refers to the probability of detecting a fault. These two measures of the inspection process can be expected to be inversely related; in other words, accuracy generally decreases as speed increases and vice versa. In particular, Teichner and Krebs (1974) and Drury (1994) have demonstrated that speed/accuracy trade-offs (SATO) are manifest in a visual search task.

While both (inspection) speed and accuracy may be improved as a result of repeated practice, the desired result can be achieved more efficiently through training (Gramopadhye and Drury, 1992). One major distinction between practice and training is that the latter includes some form of feedback, whereas the former does not. Literature on inspection cites several instances of improvement in visual inspection performance with feedback (Chaney and Teel, 1967; Cockrell and Sadacca, 1971, as cited by Embrey (1979); Drury and Addison, 1973; Czaja and Drury, 1981). Wickens (1984) states that providing feedback helps subjects pay attention to the degree of success of their strategies. [1]

Traditionally, the feedback provided has been strictly with respect to speed and accuracy. However, in some instances, a more appropriate measure of inspection performance may be in terms of the economic consequences of speed and accuracy, rather than speed and accuracy per se. Thus, it seems reasonable to hypothesize that in these instances, a more effective training strategy may be to provide feedback directly with respect to the economic consequences, rather than in the indirect form of speed and accuracy (commonly referred to as *economic* and *performance* feedback, respectively).

Moreover, the optimization of a visual search task requires a measure of overall performance. In situations where the economic consequences are not applicable (or defined), subjective judgments are required to assign relative weights to speed and accuracy (e.g., speed is twice as important as accuracy) in order to obtain this measure. On the other hand, if the economic consequences are appropriate and can be quantified, the weights assigned to speed and accuracy will be determined by these consequences.

Hence, it seems reasonable to conjecture that providing feedback directly with respect to the economic consequences, where applicable, may be more effective than the alternative in this latter context as well. Nevertheless, the outcome of such a training strategy is unclear, due to a substantial body of evidence which suggests that individuals do not give adequate weight to economic considerations (Rouse, 1981; Towne et al. 1981).

Moreover, people do not conceptualize losses and gains symmetrically (Payne et al., 1982; Tversky and Kahneman, 1981). This behavior predominantly manifests itself in three forms during decision making. First, "a potential loss of a given amount is viewed as having greater consequences and therefore exerts a greater influence... than does a gain of the same amount" (Edwards et al., 1965, as cited by Wickens, 1984). Secondly, under time pressure, individuals appear to give more weight to negative evidence than to positive evidence when comparing alternatives (Wright, 1974). Thirdly, "individuals tend to be risk-averse when choosing between potential gains of equal... value, but risk seeking when choosing between potential losses" (Payne, 1980; Payne et al., 1982; Tversky and Kahneman, 1981, as cited by Wickens, 1984). Hence, the consequences that are perceived and subsequently internalized may not correspond to the actual ones (sometimes re-

[1] Explaining this phenomenon, Annett (1966) attributed the improvements in performance to increased motivation, reinforcement of the desired response, and assimilation of the informational content (of the feedback).

ferred to as *implicit* and *explicit* consequences, respectively), which may potentially result in suboptimal decision making (Wickens, 1984).

Conversely, investigators have demonstrated that optimum performance can readily be achieved in other contexts. For example, subjects have been successful in locating the maximum (summit) of an unseen two-dimensional "hill" when feedback on the height achieved was provided (Laughery and Drury, 1979; Berkowitz et al., 1983). ("In this two-variable optimization task, a subject had to "climb" an unseen "hill" on a two-dimensional board. At each move, the subject selected x- and y-coordinates and was given the height of the hill at those coordinates. Subjects continued in a series of moves until they had found the top of the hill – the optimum value of the unseen function" (Berkowitz et al., 1983).)

In conclusion, in situations where there are explicit gains and losses and benefits associated with inspection performance, the objective is to maximize the expected gain (or equivalently, minimize the expected loss). Training interventions, in general, are certainly consistent with this objective. However, the question as to which of the two forms of feedback described above will be the most effective in this particular training context remains unresolved.

2. Model definition

In this section, a model will be described that mathematically defines the relationship between search time (i.e., speed) and accuracy. With this relationship defined, it will then be possible to develop a function for the expected gain (or loss) resulting from inspection, provided that both the explicit gains and losses associated with search performance, and the maximum search time are specified. Therewith, the optimal stopping time, or in other words, the maximum search time that optimizes the expected gain, can be determined by employing the inverse function of the expected gain. An outline of the model and a brief characterization of the visual search process follow.

The visual search of a field is typically modeled as a succession of area fixations (e.g., Bloomfield, 1975; Engel, 1977). This sequence is usually represented as being either systematic (Williams, 1966) or random (Krendel and Wodinski, 1960). The visual field may contain either a single fault, multiple occurrences of a single fault type, or multiple occurrences of multiple fault types, depending on the context.

The search task itself can be categorized as either externally-paced (e.g., machine-paced) or self-paced. In the latter case, the inspector may proceed to the next item if a fault is detected before the prescribed time period (maximum search time) elapses, whereas in the former case he or she cannot. Self-pacing is often deemed to be more suitable for inspection tasks (Drury, 1975).

The inspection task selected for this study is a self-paced random search of a visual field that contains no more than one fault of a single type. Further, it is intrinsically a "pure" search task; that is, an inspection task wherein a defect must be rejected once it is detected irrespective of the severity of the flaw. Empirically, these tasks are distinguished by an absence of false alarms (type I errors). Common examples of such tasks include spelling errors in text or wrong components on printed circuit boards (Morawski et al., 1992).

Accordingly, a model developed by Morawski et al. (1992) that is consistent with this characterization, and which has been validated specifically for inspection tasks (Drury and Chi, 1995), will be employed for the purpose of this investigation. The model is based on the underlying assumption that search time is exponentially distributed, a claim for which there is substantial empirical evidence (e.g., Bloomfield, 1975; Drury, 1990; Arani et al., 1984). Hence, the expression relating the probability of detecting a fault and the search time is given by:

$$p_t = \Pr(S \leqslant t) = 1 - \exp(-t/\mu), \tag{1}$$

where S is the search time, t the stopping time, and μ the mean search time. (Observe that as the search time increases, the probability of target detection similarly increases, indicative of the SATO phenomenon.)

The actual search time will depend upon whether the item is flawed or not, as well as whether or not (in the former case) the fault is detected. Hence, there are three outcomes of interest:

(1) the item is not flawed,

(2) the item is flawed *and* the fault is detected, and

(3) the item is flawed *and* the fault is detected.

If the item is not flawed, then the search time will necessarily be t (since false alarms are precluded in a pure search task). This will also be the case for a flawed item if the fault goes undetected. On the other hand, if the fault is detected, then the search time will assume a value less than t, hereafter denoted by S_t.

The probabilities of the respective outcomes and the associated economic consequences will ultimately determine the net gain from inspection. Both are summarized in Table 1, wherein p is the probability that a fault occurs, c the cost (loss) due to missing a fault, v the gain due to detecting a fault, and k the inspection cost per unit time.

From Table 1 it can be seen that the net gain from inspection is given by

$$E[g(t)] = -(1-p)kt - p[1-p_t](c+kt) + pp_t(v - kE[S_t]), \quad (2)$$

where

$$E[S_t] = E[S|S \leqslant t] = \mu - t(1-p_t)/p_t \quad (3)$$

since it represents the expected value of the search time given that the fault is detected by time t.

Finally, recall that the objective is to find the value of the stopping time which will maximize the expected gain (or minimize the expected loss). Morawski et al. (1992) have shown that this value, here after referred to as the optimal stopping time, is expressed as

$$t_{\text{opt}} = \mu \ln[p(v + c - k\mu)/(k\mu[1-p])] \quad (4)$$

for $(v + c > k\mu)$, and 0 otherwise.

Table 1
The probabilities and economic consequences associated with the search outcomes

Outcome	Probability	Gain
(1)	$1-p$	$-kt$
(2)	$p(1-p_t)$	$-c-kt$
(3)	pp_t	$v-kS_t$

3. Experiment

A visual search task, in the context of airframe structural inspection, was selected for the purpose of this investigation. This choice was motivated in part by the fact that this task and others in its category account for 90% of the total airframe structural inspection (Drury et al., 1990; Shepherd et al., 1991). [2]

Practical considerations precluded the use of actual airframes in this investigation. The hundreds of cracks and dents required for training, for example, would never be available to an inspector in the actual environment. Moreover, the experimental objectives require repeated exposures to these flaws within a closely controlled environment. Hence, an airframe inspection simulator, identical to that employed by Latorella et al. (1992), Gramopadhye et al. (1996) and Shepherd et al. (1991) in related studies, was employed for the experiment here. (Additional information regarding the relevant training interventions, and the associated transfer effects with respect to the validity thereof, have been reported in Gramopadhye et al., 1996; FAA 1993.)

3.1. Methodology

A description of the experimental methodology employed here, which includes detailed information regarding the subjects, stimulus material, visual search task, experimental design, training procedure, and data collection, is presented below.

Subjects. Eighteen student subjects, ranging from 20–30 years of age, participated in this experiment; the participants were financially compensated for

[2] The selection was further motivated by the fact that aircraft inspection is an important issue now, and will become even more important in the future. This will be the case because a more intensive inspection program is required as the age of the aircraft increases, since older aircraft are progressively more susceptible to the effects of fatigue cracks (especially multi-site damage) and corrosion. Presently, the average age of several types of aircraft in the United States is about 20 years (Shepherd et al., 1991), and a large-scale retirement of old aircraft is unlikely in the foreseeable future. Moreover, related maintenance and inspection costs are currently in excess of six billion dollars per year and continue to escalate (Drury et al., 1990).

their time. Engineering students were selected exclusively, since this group is representative of the technically fluent, but inexperienced, labor pool from which the aviation mechanics (who will eventually become inspectors) are drawn. Prior to commencing, the subjects were tested for 20/20 vision (corrected if necessary) and color vision.

Stimulus material. The airframe visual inspection task was simulated on a SUN SPARC workstation, a high-performance, high-resolution system (1152 × 900 pixels, 99.2 dots/inch). The input devices employed were a standard key board and an optical three-button mouse.

Visual search task. The criterion task was a self-paced visual search task wherein the subjects searched for a single type of fault (in this case, a dent) in the search field. This field represented the region of the aircraft fuselage where the aluminum alloy skin is joined by rivets. The search field was divided into nonoverlapping areas which were displayed sequentially on the screen. As each area was presented, the subjects searched for a fault for a self-determined period of time. In the event that a fault was located, the subjects so indicated by clicking the left mouse button with the cursor positioned on the target. Irrespective of the outcome, the subjects proceeded to the next screen by clicking on the *Next* button.

Experimental design. The experiment consisted of two trials, where the second trial was a replicate of the first. The second trial was preceded by a series of training exercises, during which the alternate forms of feedback were provided. Accordingly, the 18 subjects were randomly assigned to three groups: the first and second respective groups received performance and economic feedback, and the third served as a control group, and therefore received no feedback. The experiment was planned using a combined within-subjects and between-subjects design. The 3 × 2 (*groups* × *trials*) design consisted of the performance, economic, and control groups (with six subjects nested under each group), and the "before" and "after" training trials (hereinafter designated as Trials 1 and 2).

Training procedure. First, an overview of the experiment was presented to the subjects. The subjects were also shown the field to be inspected and provided with a graphical and verbal description of the fault. Then, a demonstration program was presented to the subjects in order to further familiarize them with the setup. Lastly, each subject was provided with the following economic information: the value of detecting a defect (v) equals \$3; the cost of missing a defect (c) equals \$7; and the cost of inspection per unit time (k) equals 12.5 cents/s. [3] The subjects were thereupon instructed to maximize the expected gain of inspection.

Initially, the three groups performed the criterion visual search task in Trial 1 that consisted of 150 randomly ordered search areas, 30 of which contained faults. Following the completion of Trial 1, the three groups received six training exercises, each of which consisted of 50 randomly ordered search areas with a total of 10 faults. Feedback was provided after the completion of each training exercise. Specifically, subjects in the performance group were provided with feedback on the following performance measures: hit rate (i.e., the percentage of dents detected); search time; and stopping time, and subjects in the economic group were provided with the corresponding economic losses and gains. (Naturally, the control group received no feedback.) Following the feedback exercise, the groups performed Trial 2, which was identical in content to Trial 1.

Data collection. Data was collected on the following three individual performance measures: hit rate, search time (in seconds), and stopping time (in seconds). Finally, at the end of the session, a retrospective verbal protocol was administered (i.e., each subject was asked to recall his or her search strategy, which was subsequently related to the individual's performance by the investigators.).

4. Results

The statistical analyses of the three performance measures of interest will be summarized in this

[3] The economic values employed herein were fixed after consultation with a technical training manager at an FAA approved repair facility. Specifically, they pertain to dents that are categorized as noncritical defects (according to FAA guidelines), the repair of which may be deferred. The interested reader may refer to Drury and Chi (1995) for further information regarding the behavioral implications of different economic value structures.

section. Subsequently, certain issues pertaining to the relationship between speed and accuracy are to be examined.

4.1. Performance measures

A two-factor (*Group*, *Trial*) experiment with repeated measures on one factor (*Trial*) was conducted with the three performance measures: hit rate, stopping time and search time. A multivariate analysis of variance (MANOVA) was performed since there are multiple measures, some or all of which may be correlated. Significant *Group*, *Trial*, and *Group* × *Trial* effects were evidenced through the MANOVA. Thus, univariate analyses of variance (ANOVA) were conducted for each performance measure to pinpoint the cause of these effects. In instances where the factor effects were significant, Tukey tests were performed to make comparisons among the factor levels.

Hit rate. The ANOVA indicated both a significant *Group* × *Trial* interaction ($F(2,15) = 9.32$, $p < 0.01$) and a significant *Trial* effect ($F(1,15) = 41.96$, $p < 0.001$), as illustrated in Fig. 1. Since the interaction was significant, a Tukey (a) procedure was conducted on the means (from Trial 2). The latter revealed that the mean hit rates of both the performance and economic groups were significantly greater than that of the control group. There was not, however, any significant difference between the mean hit rates of the performance and economic groups ($p < 0.05$). Lastly, the results confirmed that the task employed in the experiment was indeed a pure search task, as no false alarms were observed.

Search time. In this instance, a significant interaction was not indicated. In contrast, the *Trial* effect was highly significant ($F(1,15) = 12.22$, $p < 0.05$), as each of the three respective groups required less search time (on average) during Trial 2 than Trial 1.

Stopping time. Here, a significant *Group* × *Trial*

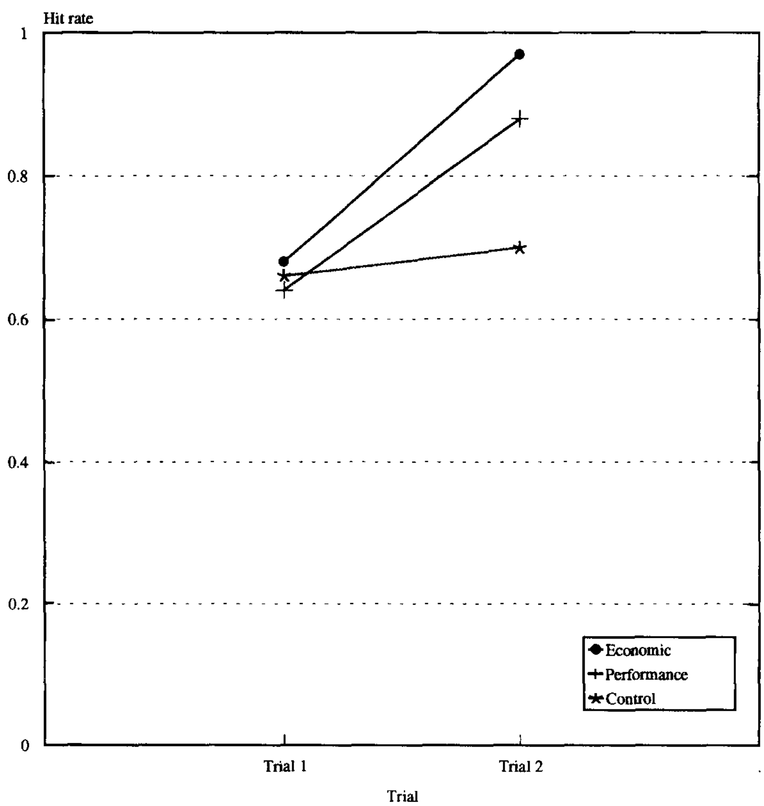

Fig. 1. Mean hit rate versus trial.

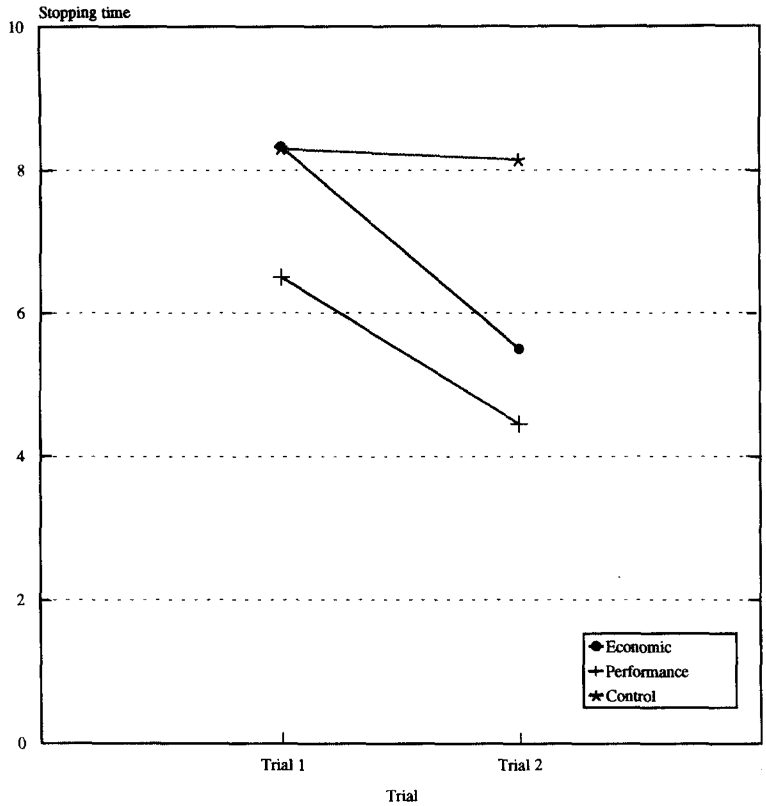

Fig. 2. Mean stopping time versus trial.

interaction ($F(2,15) = 13.79$, $p < 0.05$), a significant *Trial* effect ($F(1,15) = 42.99$, $p < 0.01$) and a significant Group effect ($F(2,15) = 10.12$, $p < 0.05$) were manifest, as seen in Fig. 2. Subsequently, the Tukey (a) test showed that the average stopping time for the performance group was significantly less than that of the economic group and that the control group had a mean stopping time that was significantly greater than that of either of these two groups ($p < 0.05$).

In addition, in order to compare the actual mean stopping times with the optimal stopping time (as prescribed by the model in Eq. (5), an ANOVA was performed on the relative percentage differences. [4] The mean stopping times for all the groups were substantially greater than the optimal time in Trial 1, as depicted in Fig. 3. While this was also the case for the control group in Trial 2, the mean stopping times recorded for the performance and economic groups were then *less* than the optimal time. In general, the degree to which these times differed decreased from Trial 1 to Trial 2. Lastly, no significant statistical differences were observed *between* the groups in Trial 1; however, the opposite was true for Trial 2 ($F(2,15) = 12.51$, $p < 0.01$).

4.2. Speed / accuracy trade-off

Recall that previous investigators have reported the existence of a speed/accuracy trade-off in visual search tasks. Moreover, the distribution of search times in this context has been satisfactorily modeled with an exponential density function. The extent to which these relationships are evidenced in this study are reported herein.

First, a correlation analysis was conducted in order to determine the degree of association between

[4] $100\%(\bar{t}_i - t_{opt})/t_{opt}$, for $i = 1, 2, 3$, where $\bar{t}_i$ denotes the average stopping time of the i^{th} group.

speed and accuracy. This analysis demonstrated significant association between the stopping time (speed) and corresponding hit rate (accuracy) data for both Trial 1 ($r^2 = 0.671, p < 0.025$) and Trial 2 ($r^2 = 0.73, p < 0.025$), which is consistent with the results of prior studies.

Subsequently, regression analyses were performed to ascertain whether or not an exponential distribution function (Eq. (1)) was a suitable model for the relationship between speed and accuracy. Separate analyses were conducted for the two trials so that the performance of the subjects *before* and *after* training could be differentiated (and eventually, contrasted). Thus, the data collected from the control group in Trial 2 was excluded (as this group received no training).

The parameter of the exponential distribution, μ, which corresponds to the mean search time, was estimated with a pooled sample mean in both trials. The respective estimates obtained for these trials were 6.94 and 1.82 s. Subsequently, the regression analysis verified the adequacy of the exponential model both for Trial 1 ($r^2 = 0.90, p < 0.001$) and Trial 2 ($r^2 = 0.94, p < 0.05$).

5. Discussion

The manner in which feedback affected the behavior of the different groups was determined by analyzing the results and verbal protocols. The analysis revealed that the performance and economic groups both required less time to detect faults (on average) and detected a greater number of faults than the control group. These results are consistent with those of past researchers who found that providing feedback both reduced search time and improved accuracy (Chaney and Teel, 1967; Czaja and Drury, 1981).

Nonetheless, the trade-off *between* speed and ac-

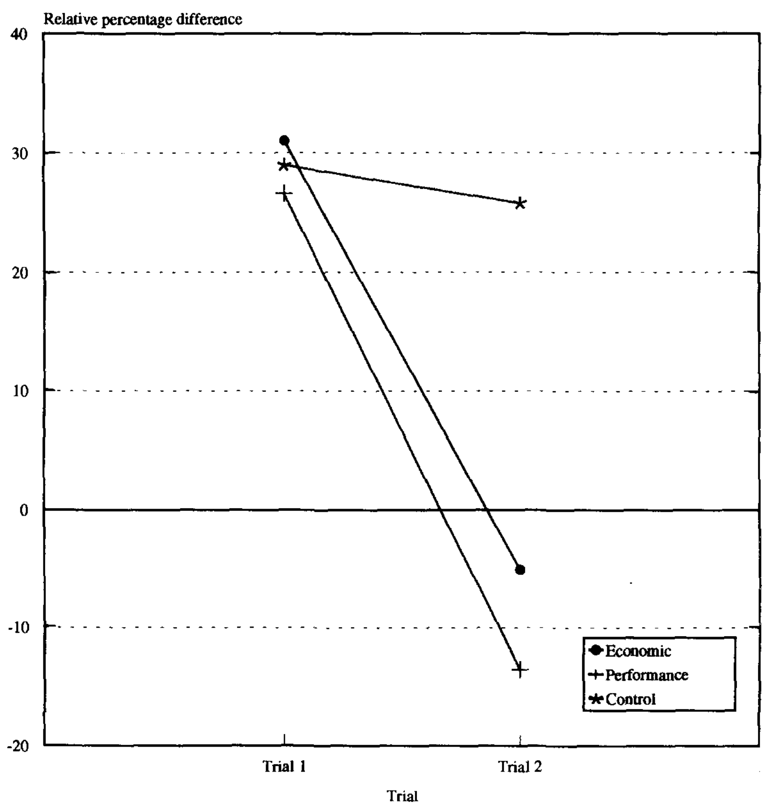

Fig. 3. Relative percentage difference versus trial.

curacy was less than satisfactory, as the average stopping times of these groups were less than the optimal value. This outcome suggests that the relative value of speed conceptualized by the subjects was greater than that defined by the economic consequences. This tendency, however, was less evident in the economic group.

It is reasonable to assume that the subjects conceived the relative importance of speed and accuracy when they were apprised of the cost/value structure. Performance feedback did not allow the subjects to alter this preconception. Conversely, economic feedback permitted the subjects to evaluate their performance in this regard and adapt their strategy accordingly.

In contrast to the performance and economic groups, the average stopping time of the control group was greater than the optimum. It is conjectured that this occurs because, in the absence of any feedback, control group subjects are not able to evaluate the effectiveness of their search strategy. Consequently, subjects tended to behave more conservatively and scan the areas for a longer period of time before stopping. This conclusion, as well as those above, is consistent with statements that were made during the administration of the retrospective verbal protocols.

The visualization of the interrelationship between speed and accuracy is facilitated by the use of a speed/accuracy operating characteristic (SAOC) curve, which is simply a graphical representation of the exponential distribution function. Accordingly, the regression functions fitted in the previous section, now depicted in Fig. 4, will be considered here once again. The mean hit rates of the performance, economic, and control groups, both before and after training, have also been plotted as a function of the stopping time for later reference.

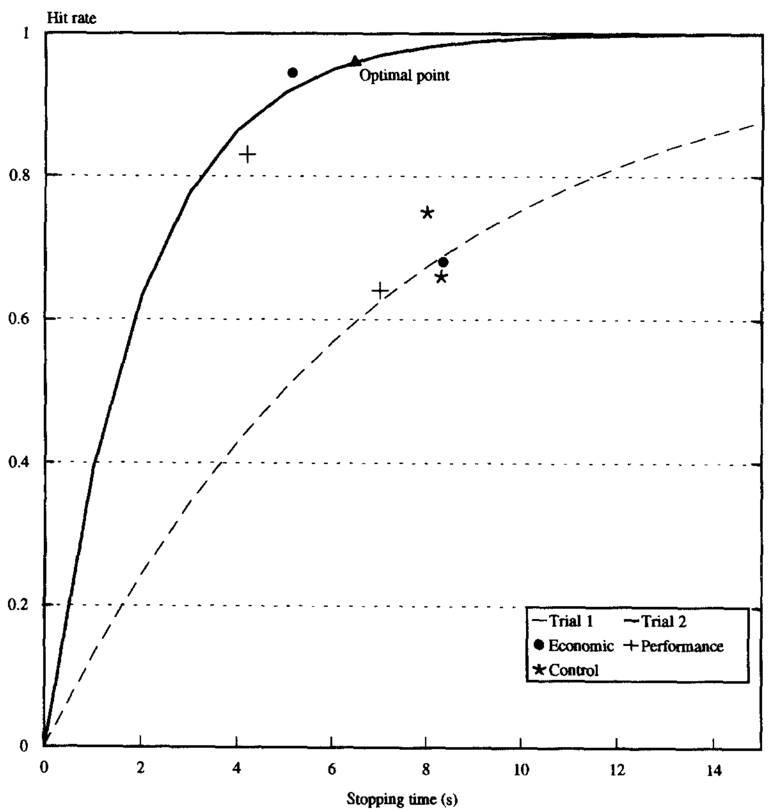

Fig. 4. Speed/accuracy operating characteristic curves.

First, observe that the SAOC curve has shifted leftward and upward markedly, reflecting the degree to which the feedback received during the training exercises has served to improve speed and accuracy, respectively. (In contrast, note the relative position of the mean of the control group, which reflects the level of improvement that may be achieved through pure practice alone.) The speed/accuracy trade-off is evident from this curve, from which it can be seen that as the stopping time increases, the hit rate increases, and vice versa.

The optimal stopping time, also shown in Fig. 4, is fixed by the relative economic values of speed and accuracy. Notice that while the mean of the economic group does not coincide with the optimum, it is positioned more closely thereto than the mean of the performance group. Thus, although the performance of the economic group was not optimal, it nevertheless can be seen that the subjects were able to utilize the economic feedback to effect a ''better'' (that is, more optimal) strategy than their counterparts. This finding is consistent with that of Wickens (1984) and Drury (1990), who have reported that subjects can behave as ''optimizers'' or at least as ''degraded optimizers'' for certain inspection tasks (e.g., printed circuit board inspection (Drury and Chi, 1995)).

Finally, this study has several implications related to the design of training programs for certain aircraft inspection and maintenance tasks. While safety is of paramount importance, there is considerable competitive pressure to decrease the time devoted to maintenance and inspection in order to both reduce the associated costs and meet departure schedules. It has been demonstrated herein that providing feedback during training supports these oftentimes conflicting goals by serving to increase both accuracy and speed. However, performance feedback apparently leads to ''risk seeking'' behavior, as these subjects exhibited a bias towards speed (at the expense of accuracy). Economic feedback, on the other hand, mitigated this bias to a significant extent, by apprising the subjects of the negative consequences of their strategies. (Further, it is conjectured that ''risk averse'' behavior could be engendered by weighting the values of the gains and losses accordingly.) This particular form of feedback also allows the subjects to alter their strategies in order to minimize the associated costs.

6. Conclusion

In this study, performance and economic feedback were compared in a simulation of an inspection task. The particular activity selected is intrinsically a pure search task, the outcomes of which have known economic consequences. The comparison revealed that the feedback provided during training led to significant overall improvements in speed and accuracy, whereas practice alone did not. However, the subjects that received economic feedback were better able to recognize and adapt to the economic consequences of their strategies, and hence were more effective in balancing the respective consequences of speed and accuracy. In the context of the aircraft inspection task, the results suggested that if the applicable training programs were to include economic feedback, rather than traditional performance feedback, inspection-related costs could be reduced without sacrificing accuracy.

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